REPORT DOCUMENTATION PAGE

Form Approved
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1. REPORT DATE *(DD-MM-YYYY)*
06-02-2006

2. REPORT TYPE
Journal Article

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

Investigations of an Environmentally Induced Long Duration Hall Thruster Start Transient (PREPRINT)

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
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5d. PROJECT NUMBER
10110011

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
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8. PERFORMING ORGANIZATION REPORT NUMBER

AFRL-PR-ED-JA-2006-073

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory (AFMC)
AFRL/PRS
5 Pollux Drive
Edwards AFB CA 93524-7048

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S NUMBER(S)
AFRL-PR-ED-JA-2006-073

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited (AFRL-ERS-PAS-06-057)

13. SUPPLEMENTARY NOTES
Submitted for publication in Journal of Propulsion and Power

14. ABSTRACT
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15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Dr. William A Hargus, Jr.
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**	A	20	**19b. TELEPHONE NUMBER** *(include area code)*
Unclassified	**Unclassified**	**Unclassified**			N/A

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. 239.18

Investigations of an Environmentally Induced Long Duration Hall Thruster Start Transient (Preprint)

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Abstract

A long duration Hall thruster start transient is produced by exposure of the thruster to ambient laboratory atmosphere. This behavior was first observed during operation of a cluster of four 200 W BHT-200 Hall effect thrusters where large anode discharge fluctuations, visible as increased anode current and a diffuse plume structure, occurred in an apparently random manner. During operation of a single thruster, the start transient appears as a quickly rising and later smoothly decaying elevated anode current with a diffuse plume that persists for less than 500 seconds. The start transient is characterized by severe 18 kHz oscillations that dominate the anode discharge. This contrasts sharply with typical steady state behavior of a strong DC component overlaid with a low amplitude 25 kHz component. The source of the plasma oscillations has been isolated to the discharge chamber. The oscillations of the anode current appear to be due to the evolution of water previously hydrated onto the surface layer of the boron nitride acceleration channel insulator during exposure of the Hall effect thruster to ambient atmosphere. Once all available water has been driven from the insulator surface by plasma heating, the discharge fluctuations do not reappear.

Introduction

During testing of a cluster of four Busek Company, Inc. 200 W BHT-200-X3 Hall effect thrusters at the Air Force Research Laboratory (AFRL) Electric Propulsion Laboratory at Edwards AFB, CA, large amplitude oscillations of the anode currents occurred regularly during the first start following evacuation of the vacuum facility. The

oscillations manifest themselves visibly as the thrusters variously enter and exit *jet mode* over time scales of several seconds. Jet mode is associated with high efficiency operation of the BHT-200-X3 and is characterized by a clearly visible jet-like plume structure extending 5-10 thruster diameters. When the thrusters are not in jet mode, they operate in a regime with a significantly higher discharge current characterized by a diffuse plume, referred to here as *diffuse mode.*

In the AFRL cluster, the mode transitions are sometimes synchronized between several thrusters. Two, or more, thrusters may enter jet mode simultaneously; or alternatively, exchange diffuse and jet modes. The behavior appears to be random with thrusters transitioning between the preferred jet mode and the less efficient diffuse mode with a higher discharge current. Once the cluster is operated for more than 500 seconds, the oscillatory behavior disappears and does not reappear in subsequent starts; however, when the chamber is returned to ambient atmospheric conditions and subsequently evacuated, this behavior reappears.

During operation of a single thruster, the start transient due to these current oscillations is regular and repeatable. The anode discharge current immediately after start is near nominal, followed by a rapid rise to approximately 150% nominal anode current, and a gradual decrease to the nominal value. Unlike the cluster, there is no evidence of multiple plume mode changes during operation of a single thruster. In order to better understand this phenomenon, a detailed examination of the start transient of a single thruster is presented.

Hall Thrusters and Test Facilities

The Busek Company, Inc. BHT-200-X3 Hall effect thrusters used for this test are described in detail elsewhere [1, 2]. The thrusters are operated at an anode discharge power of 200 W with a 250 V discharge potential. For all results described here, the cathode heater and keeper discharge remain powered to minimize the possibility of thruster oscillations extinguishing the anode discharge. A cluster of four of these thrusters is available at AFRL and is used to determine the general engineering aspects of

clustering Hall thrusters. A photograph of the cluster is shown in Fig. 1. The thrusters are placed in a 2x2 grid with a center-to-center separation of 115 mm.

Each BHT-200 thruster in the cluster is independently connected to four power supplies. A Sorensen DHP-400-5 is used for the main discharge, a Sorensen DCS-600-1.7E is used to power the cathode keeper, and two Sorensen DLM-40-15's provide power to the magnetic circuit and cathode heater. During all testing, the thruster is operated at the nominal conditions shown in Table 1. Following exposure of the thrusters to ambient atmospheric conditions, the cathodes of each thruster are conditioned by flowing 98 µg/s of xenon and a heating sequence of 90 minutes. An inductive-capacitive (L= 250 mH, C = 13 mF) filter is used to provide isolation of the power supplies from the discharge oscillations of the plasma and to minimize feedback. Measurements show that the LC circuit shields the power supplies' exposure to plasma oscillations by 30-50 dB.

Xenon propellant (99.995%) flow to the thrusters is metered by use of Unit Instruments model 7301 digital mass flow controllers (MFCs) calibrated for xenon (± 1%). Flow through each anode and cathode is individually metered by a separate MFC. Ten thruster electrical operating parameters are recorded for each thruster during operation of the system using an Agilent 34970A data acquisition and switch unit. These parameters include the currents and potentials of the anode, cathode, heater, keeper, and magnet circuits. These data are taken at approximately 1 Hz.

All measurements in this study were performed in Chamber 6 at the AFRL Electric Propulsion Facility at Edwards AFB, CA. Chamber 6 is a stainless steel chamber with a 1.8 m diameter and 3 m length. It has a measured pumping speed of approximately 30,000 l/s on xenon. Pumping is provided by four single stage cryogenic panels (APD single stage cold heads at ~25 K) and one 50 cm two stage APD cryogenic pump (<12 K). The chamber is roughed by an oil-free mechanical pump and blower. The chamber is configured such that the 50 cm cryogenic pump may be isolated from the chamber and cryo-panels. During the pump down of the chamber, the chamber is first roughed to approximately 4 Pa using the mechanical pump and blower. At this time, cryogenic panel

cooling begins. When a single thruster is operated, the background xenon pressure measured by a cold cathode vacuum gauge is $7x10^{-4}$ Pa.

Experimental Observations and Analysis

Figure 2 shows the anode current of a near simultaneous start of the four thrusters in the cluster following chamber pump down and cathode conditioning. The thrusters variously enter and exit jet mode (characterized by a nominal anode current of approximately 0.8 A) and the diffuse mode (characterized by higher anode currents). After approximately 500 seconds, the start transient disappears and does not return in subsequent restarts; however, the transient does return following exposure to ambient conditions. The general behavior of this start is repeatable, but not the precise sequence of mode transitions.

Unlike the cluster, the start transient of a single isolated thruster following exposure to ambient atmospheric conditions is readily repeatable. The thruster begins operation near the nominal anode discharge current. The discharge current then rapidly rises to a maximum, typically 150% nominal. This is followed by a gradual decrease to nominal discharge current. During the start transient, the plume is diffuse and does not enter jet mode. Once the thruster has reached near nominal anode current, the thruster then enters jet mode.

Figure 3 shows a typical trace of the anode current during a start after the thruster has been exposed to atmosphere. The initial anode current spike (1.5 A) is due to the start procedure where the anode discharge is current limited and the magnet current is off. After the magnet current is switched to its nominal value, the anode current rapidly rises to 150% nominal (1.2 A). It then gradually decays to the nominal value of approximately 0.8 A. The start transient only occurs for the first 300-500 seconds of operation and does not return on restart once the thruster has been fully conditioned. With subsequent atmospheric exposure, the start transient returns. Figure 4 shows that this behavior persists even if the thruster anode discharge is cycled during the time period associated with the transient. Interestingly, the thrust level during the period of the anode current

transient is unchanged. The 50% increase in anode current simply reduces thruster efficiency due to an increase in electron current [3].

The start transient has two distinct precursors. First, it occurs when the chamber has been opened to atmosphere, exposing the thrusters to atmosphere. Second, it occurs when the chamber pumps have been turned off, allowing the cryo-panels to regenerate, exposing the thrusters to a 70 Pa atmosphere primarily consisting of xenon sublimated from the cryo-panels and water which was trapped by the panels during the initial pump down. Subsequent use of the chamber does not require pressurization to atmosphere. The chamber may be mechanically roughed to approximately 3 Pa at which time the cryogenic pump and cryogenic panels are activated.

The duration of the start transient may be correlated directly to the degree of exposure to the atmosphere, or gases sublimated from the pumping surfaces. If exposed to atmospheric conditions for several days, the anode current will return to the nominal 830 mA anode current within 500 seconds. Subsequent exposures to regenerated vacuum appear to reduce the length of the anode current transient by approximately 20%. For example, thruster 1 was started after exposure to atmosphere and the initial transient persisted for 425 seconds. The chamber was cycled without being opened to atmosphere and the subsequent start transient lasted 340 seconds. This chamber was again cycled without being opened and the start transient persisted for only 255 seconds. In another case, when the chamber is brought up to atmosphere for approximately 20 minutes, the duration of the start transient was less than 30 seconds. These trends appear typical of all four thrusters.

There is a secondary oscillation in Figs. 3 and 4. The start transient is accompanied by a periodic (~60 sec) drop in the anode current. Figure 4 shows quite clearly that this period is not affected by the thruster on/off condition. This behavior has been correlated to the pressure fluctuations in the propellant lines of the thruster due to the spring action of the single stage pressure regulator. The effect has been documented previously and is known issue with thermal MFCs [4]. Due to the low flow of propellant from the pressure bottle through the MFC, the single stage pressure regulator between the

high pressure xenon bottle and the MFC is opening producing a periodic pressure spike. The valve on the single stage regulator then closes until the pressure drops by some fraction of the set pressure and then the process cyclically repeats. The MFC responds to these periodic increases in upstream pressure and overcompensates, reducing the flow. This overcompensation is due to the flow sensing element being upstream of the throttling valve in the MFC. The MFC does not recognize that it has overcompensated and for approximately 3 seconds the flow is reduced by approximately 10%, reducing the anode current by a similar fraction. This effect is not apparent when a flow greater than 3x that of a BHT-200-X3 is metered; therefore, it does not appear in Fig. 2. This periodic pressure spike was later minimized by replacing the single-stage pressure regulator with a two-stage pressure regulator. Caution should be taken not to confuse this facility issue with the thruster start transient. The two effects appear to be independent.

Frequency spectra of the start transient anode current oscillations during a thruster start measured using Tektronix TCP202 current probes and an TEK1103 probe power supply connected to an Stanford Research Systems SR785 dynamic signal analyzer (DC-104 kHz) are shown in Fig. 5 where the oscillatory behavior during the start transient is compared to the steady state behavior. During the start transient, there is a strong oscillation at 18 kHz and 4 harmonics. This behavior is radically different than the steady state behavior. During steady state, there is only a single broad peak at approximately 25 kHz. The steady state spectrum is also significantly less energetic with peak magnitudes approximately 20 dB less than the start transient.

Figure 6 shows the time evolution of the anode current frequency spectrum during the start transient. Although the frequencies of the major features are increasing slightly and the harmonics are decreasing in magnitude, these frequency components retain significant power until they abruptly collapse into the lower amplitude steady state single broad peak at 25 kHz. The periodic shifts in the peaks correspond to periods of lowered propellant flow during the single stage pressure regulator’s approximately 60-second cycle.

The time domain behavior during the start transient and steady state are also very different. Examination of the anode current using two Tektronix TCP202 current probes connected to a Tektronix TDS3012 100 MHz bandwidth oscilloscope is shown in Fig. 7. It shows the dramatic difference between the steady state behavior and the behavior during the anode current transient. During steady state, there is a strong DC anode current component overlaid by a weak 25 kHz component. The behavior during the start transient is nearly the opposite. The anode current is primarily AC with peaks measured as high as 9 A. In this mode of operation, the anode discharge is turning itself on and off every 50-60 μs.

The most surprising result is the difference in the acceleration channel current conduction between the start transient and steady state. These two cases represent distinct operating conditions. In steady state operation, the small amplitude approximately 25 kHz frequency component is generally attributed to the so-called breathing mode oscillation. [5]. Here, the ionization occurs in a planar sheet that oscillates transversely within the acceleration channel. The frequency of which is related to the neutral residence time (25 kHz = 40 μsec). During the start transient, an amplified breathing mode oscillation appears to dominate the anode discharge.

Experiments demonstrate that the anode discharge is responsible for the start transient. The cathode may be eliminated as the cause of the start transient by operating a thruster until the thruster is fully conditioned (following operation for more than 500 seconds), then firing that anode discharge with a cathode of a second adjacent thruster. This produced no evidence of the start transient. The second thruster was subsequently started (using its previously operated cathode), and it produced a typical start transient. This exercise shows that the anode discharge is the portion of the thruster affected by exposure to atmospheric conditions.

An examination of the anode discharge chamber of the Busek BHT-200-X3 Hall thruster (similar to many other Hall thrusters) reveals that the portions of the thruster in contact with the plasma are limited to the alumina plasma sprayed coated front plate of the magnetic circuit, the iron anode, and the boron nitride (BN) acceleration channel

insulator. Of these three surfaces, the most likely to be affected by exposure to ambient laboratory conditions are the BN insulator inserts due to their high porosity (~15%) and a thermodynamic tendency to hydrate. Some BN grades are capable of absorbing up to 3.5% of their weight in water in conditions of high relative humidity. Higher purity grades generally absorb less water (<1%). The hydration is believed to be primarily a surface phenomenon, but the depth of penetration is unknown. In general, the hydration of BN may be reversed by heating. For example, one manufacturer, suggests heating their BN products to approximately 400°C for one hour to reverse hydration caused by exposure to ambient atmospheric conditions [6].

It appears that the plasma within the acceleration channel is either etching away the hydrated layer of the insulator, or more likely, the plasma is heating the hydrated surface and driving the water out of the BN matrix. Xenon ion recombination (12.1 eV/ion) as well as kinetic energy (here as high as 200 eV) is deposited on the wall surface by each ion impact, substantially locally heating the surface. Despite the high thermal conductivity of BN, most areas of the accelerator channel wall will be periodically heated to extremely high temperatures. This will drive water molecules from the BN matrix. Considering the time scale of 300-500 seconds, this appears to be the most likely scenario.

In order to test the hypothesis that the start transient is due to water liberated from the insulator walls via plasma heating, two sets of emission spectroscopy experiments were performed. The first used an Ocean Optics USB-2000 fiber optic spectrometer where emission was collected from the Hall thruster anode discharge at approximately 45° to the plume centerline through a quartz window. The emission was focused by a 25 mm diameter lens onto a fiber optic launcher which then routed the light to the spectrometer. Spectra from the anode discharge (400-1000 nm) were gathered at 30 second intervals to determine changes in emission during the start transient. Figure 8 shows two characteristic spectra. The uppermost is of the discharge during the start transient when the anode current is near maximum (1.20 A). The second spectrum is at 720 seconds after which the anode current has reached its nominal value (830 mA). Each

emission spectrum represents 100 averaged samples with 5 ms integration times. The spectra are not intensity calibrated.

Upon examination of Fig. 8, it is evident that the two spectra exhibit significant differences. Several of the strongest neutral xenon lines (823 and 882 nm) increase in intensity, and some (828 nm) decrease slightly in intensity. Interestingly, the ionic xenon lines that form the bulk of the emission below 600 nm are of much lower intensity for the steady state case than during the start transient.

There are several possible explanations for the decrease in xenon ion emission. First, the electron temperature of the plasma may be higher during the transient period. The 18 kHz enhanced breathing mode with high instantaneous anode currents produces strong, periodic electric fields within the acceleration channel. This may raise the bulk electron temperature and increase the density of excited state ions and thereby the emission from the excited states seen in Fig. 8. Since the anode current is as much as 150% of nominal, the electron density also is likely much higher within the acceleration channel. The oscillations also enhance electron conductivity allowing higher energy electrons into the vicinity of the anode. These results of the start transient may result in an increase the populations of ionic excited states.

Figure 9 shows the emission time history of three representative xenon transitions. The xenon ion transitions are well characterized by the $5d\left[3\right]_{7/2}-6p\left[2\right]^{0}_{5/2}$ transition at 605 nm. All sampled ionic transitions tend to follow its general behavior. It is characterized by an initially very low value when the anode discharge is in a glow discharge mode with the magnetic current at zero. As soon as the magnets are energized, the emission rises to its largest value and then decays to a value of approximately 40% of maximum once the start transient dissipates at 400 seconds.

The neutral line intensities appear to fall into two broad categories as shown in Fig. 9. The first is represented by the $6s\left[3/2\right]^{0}_{1}-6p\left[1/2\right]_{0}$ transition at 828 nm where the lower state is radiatively coupled to ground state, and the second by the $6s\left[3/2\right]^{0}_{2}-6p\left[5/2\right]_{3}$ transition at 882 nm where the lower $6s\left[3/2\right]^{0}_{2}$ state is metastable

with a lifetime of 43 seconds [7]. In both cases, the signal is at its peak value during the initial glow discharge. At 400 seconds once the anode current has reached steady state, emission from both transitions reach 50% of that during glow discharge. However, their behavior is very different during the start transient. Neutral transitions which are optically coupled to the ground state immediately drop to an intermediate value which remains near constant during the start transient, except for a small rise just prior to the anode current reaching steady state. When the anode current reaches steady state (400 seconds), the emission drops suddenly to its final value. Alternatively, transitions with metastable (MS) lower states (i.e. not optically coupled to lower states) exhibit different behavior. After the magnetic circuit is energized, the emission level drops further than the other neutral case. The emission level then rises to its steady state value once the thruster transitions out of the start transient.

In Fig. 9, the neutral relative intensity ratio during the initial glow period and steady state are the same, indicating the upper states of these transitions are similarly populated. This implies that the neutral temperature is also likely to be very similar. That the intensity ratios differ during the start transient implies that the neutral xenon temperature is different, likely higher. By only examining these highly excited states and without greater knowledge of the equilibrium state, any further discussion is unfortunately purely speculative.

A 0.75 m focal length vacuum UV monochrometer (Acton model 704) was placed normal to the plume centerline and sampled the exit plane emission. Figure 10 shows the atomic hydrogen Lyman alpha emission (122 nm) collected during the start transient relative to the excess anode current (defined as actual current minus nominal current). Also included in the plot is the emission signal of the atomic hydrogen Balmer alpha transition (656 nm) acquired by the fiber optic spectrometer.

Figure 10 shows that both hydrogen emission profiles follow the anode current in excess of nominal closely, further reinforcing the hypothesis that the excess anode current during the start transient is due to water vapor released into the discharge channel. Subsequent restarts do not produce measurable hydrogen emission. Figure 10 implies a

strong correlation between the emission of hydrogen and the excess anode current. The near constant intensity ratio between the two hydrogen transitions indicates that the atomic hydrogen temperature is not changing significantly during the start transient. This behavior is consistent with the neutral xenon emission in Fig. 9.

If the rise in anode current during the start transient is only a function of the volumetric flow rate, an additional 5 standard cubic centimeters per minute (sccm) volumetric flow would provide sufficient charge carriers to raise the anode current by 50%. With the simple assumption that the excess anode current is solely due to the influx of water vapor liberated from the insulator walls, it is possible to estimate the quantity of water released by the start transient. A water vapor flow rate of 5 sccm of 500 seconds duration with a 50% duty cycle yields a total mass of 17 mg. This is a maximum value since each atom in the water molecule could conceivably be ionized and accelerated by the anode discharge. Assuming a 1% hydration (the maximum for higher purity grades of BN) and a typical density of 1.8 g/cm^3, approximately 1 cm^3 of BN is hydrated. The total BN surface area exposed to the plasma in the anode discharge in the BHT-200-X3 Hall thruster is approximately 14 cm^2. This yields an average depth of penetration of approximately 700 µm. This is the representative depth of hydration when the BN insulator is exposed to atmospheric conditions (generally less than 20% relative humidity at Edwards AFB, CA). It may also be the depth to which the plasma is able to drive out water vapor.

This hydration depth calculation should be viewed only as an estimate and is likely high by a factor of 3, or more, since dissociation of the water molecules has been neglected. It is unlikely that the increase in anode current during the start transient is only due to additional volumetric flow. Low frequency oscillations are known to strongly affect the electron diffusion across magnetic field lines [5]. Furthermore, the effect of light atoms/ions introduced into the xenon discharge of a Hall thruster is not well understood [8]. Laboratory experience with Hall thrusters operated on xenon contaminated with air exhibit higher than expected discharge currents accompanied by strong discharge oscillations. Therefore, it may be that the addition of a light gas into the anode discharge produces an effect much greater than its actual flow rate would predict.

Conclusions

The start transient of a Hall thruster previously exposed to ambient laboratory atmosphere or a water vapor dominated rough vacuum appears to be the result of water being driven from the BN insulator by plasma heating. The start transient only occurs within the first 500 seconds. After the thruster has been conditioned, subsequent restarts without exposure to water vapor, do not exhibit the start transient. The generation of water into the anode discharge has a destabilizing effect on the discharge and dramatically lowers thruster efficiency due to an increase in electron current. The cross field electron conductivity is significantly higher due to a high amplitude breathing mode oscillation that dominates the anode discharge during the start transient. The effect of water vapor is believed to be more than the simple addition of increased volumetric flow. Although the exact mechanism is not presently understood, the introduction of light atoms/molecules/ions appear to strongly affect the xenon discharge.

For single thruster operations, the start transient can generally be neglected as is typically done in the laboratory. Station-keeping systems with lifetimes of thousands of hours may neglect the first 500 seconds of degraded performance. Systems that may not be able to neglect this behavior are smaller satellite systems that are launched en-masse. These systems may require short duration firings with well known impulses to accurately place formations of satellites into precise orbits shortly after launch. The increasing interest in the space community in distributed architectures indicates that this issue may have to be assessed by the spacecraft community.

For a cluster of Hall thrusters, the difficulties associated with the start transient may be eliminated by operating each individually to condition each thruster independently. Once conditioned, the start transient fluctuations do not return. This option works well in the laboratory, but may not in orbit due to spacecraft dynamics. The mechanism governing the behavior of the current transient on a cluster of Hall thrusters firing in close proximity requires further examination. There is still no understanding as to the mechanism which results in thrusters variously entering and exiting jet mode during an unconditioned cluster start.

Acknowledgements

The author would like to thank Professor Cappelli and Dr. Gascon of Stanford University for the loan of the two spectrometers used in this study, as well as Dr. Katz of JPL for his comments and thoughts concerning this phenomenon.

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Tables

Table 1. Nominal operating conditions for the Busek Company, Inc. BHT-200-X3 200 W Hall thruster during these tests. Note the cathode keeper and heater remained on during these tests to enhance thruster stability.

Anode flow	840 µg/s
Cathode flow	98 µg/s
Anode potential	250 V
Anode current	0.83 A
Keeper current	0.50 A
Magnet current	1.0 A
Heater current	3.0 A

Figures

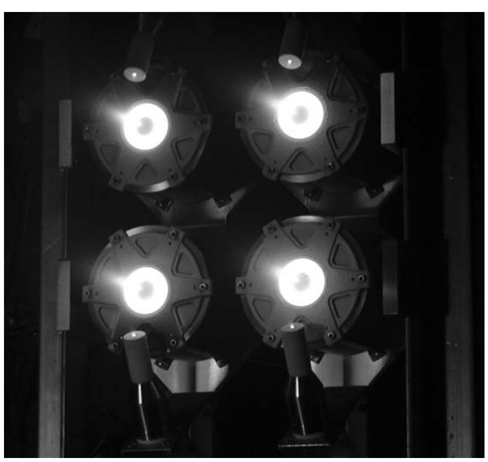

Fig. 1. BHT-200-X3 Hall thruster cluster in vacuum Chamber 6 at the Air Force Research Laboratory at Edwards AFB, CA.

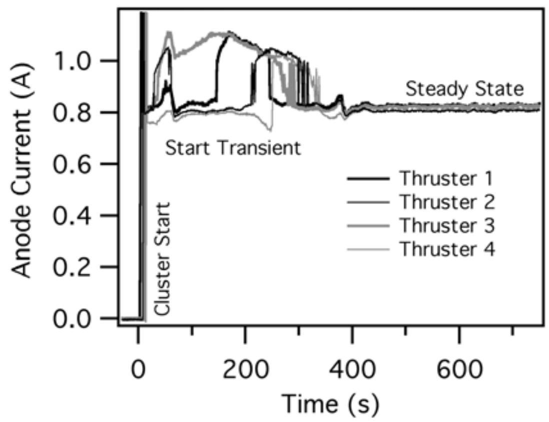

Fig. 2. Anode current data for a near simultaneous start of the cluster of four BHT-200-X3 thrusters following exposure to atmosphere. Note the initial 400 seconds exhibit the shifts between diffuse and jet modes some of which appear to affect neighboring thrusters.

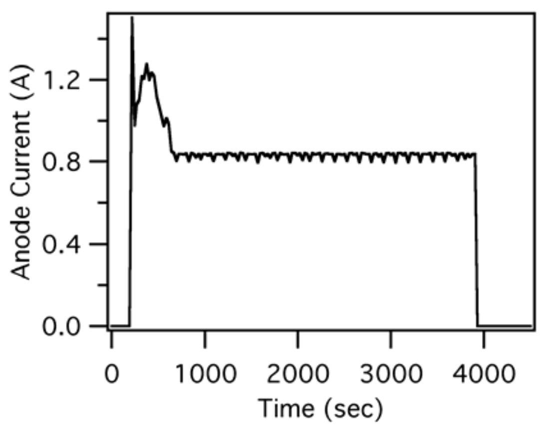

Fig 3. Anode current data showing a 420 second start transient of a single thruster following exposure to laboratory ambient laboratory conditions for several days. Note that unlike the multiple thruster case, this case exhibits a smooth transient without abrupt transitions between jet and diffuse modes.

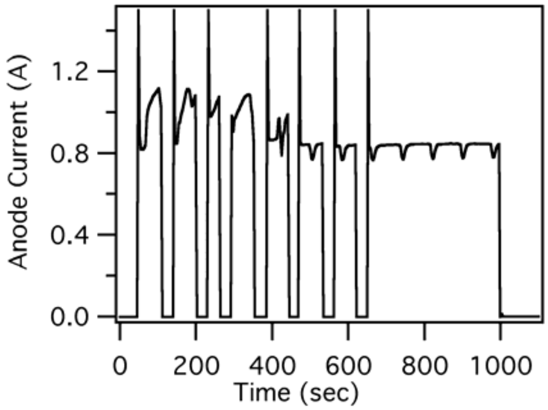

Fig. 4. Anode current data with a number of nominally 60 second firings spaced 30 seconds apart. The start transient persisted for approximately 255 total seconds. Note that in this case, the thruster was exposed to regenerated cryo-panel products for a period of 12 days following an multi-hour firing.

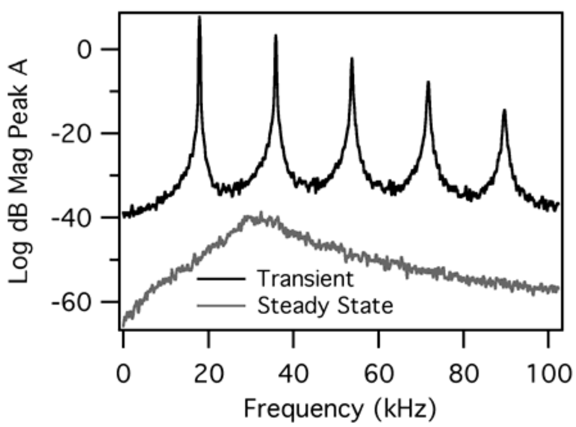

Fig. 5. Two frequency spectra of discharge current oscillations. The upper is during the start transient with an average anode current of 1.14 A, and the lower is during steady state operation with an average current of 0.84 A.

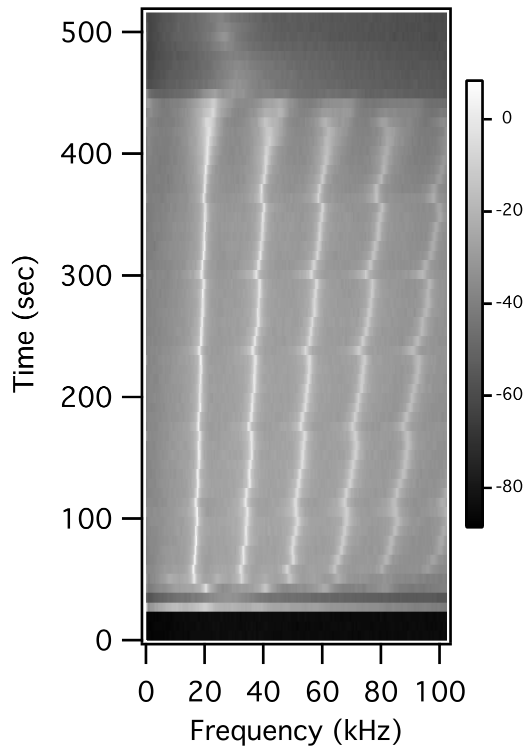

Fig. 6. Plot showing the time evolution of the anode logarithmic magnitude peak current (dB) during the start transient. Note the abrupt transition at 450 seconds where the thruster transitions from diffuse to jet mode.

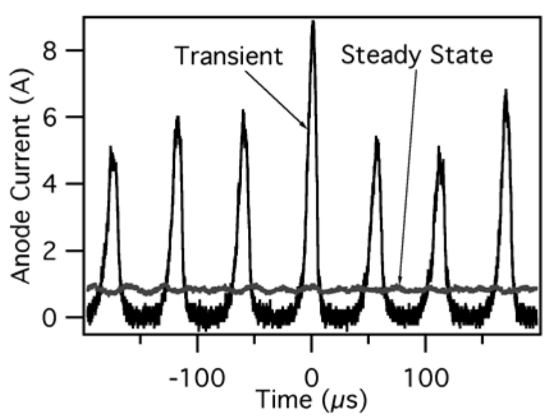

Fig. 7. Current oscillations of the transient and steady state cases. Note that during the start transient, the discharge is switching itself off and on with an approximately 30% duty cycle. Thruster conditions are analogous to those in Fig. 5.

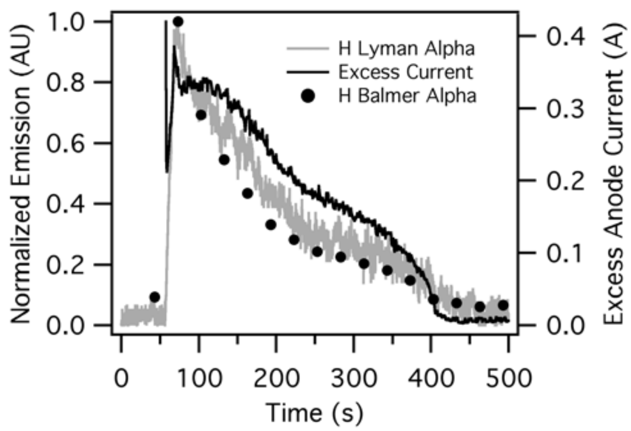

Fig. 10. Normalized atomic hydrogen emission (Balmer and Lyman alpha transitions at 656 and 122 nm) compared to the excess anode current during the start transient. Note that the excess current is defined as the actual current minus the steady state current.

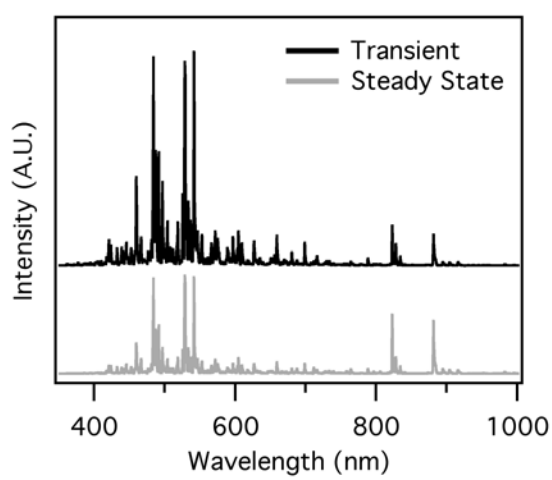

Fig. 8. Uncalibrated visible spectrum of the main discharge. The upper spectrum is representative of the start transient, while the lower is that of steady state operation. Note that the ion emission (400-600 nm) is stronger during the start transient. However, the

readily identified neutral emission (primarily 823, 828 and 882 nm) is uncharged or increases in steady state operation.

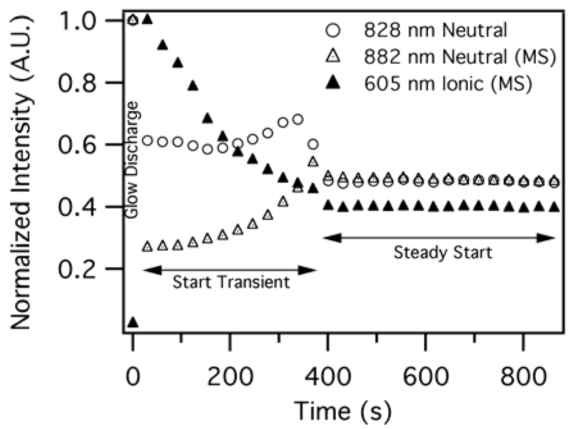

Fig. 9. Normalized representative line intensities for neutral xenon (828 nm transition with a radiative path to the groundstate and 882 nm transition with a metastable lower state) and ionic xenon (605 nm transition with a metastable lower state) during the start transient. Upon transition to jet mode (400 seconds), the emission reverts to its steady state value. Note that the emission time history of neutral xenon transitions appears to depend on whether the lower state is metastable. The emission of ionic xenon shows no such correlation.